Progress in Mo/Si multilayer coating technology for EUVL optics

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ABSTRACT

Extensive optimization on the fabrication of Mo/Si multilayer systems is carried out at the FOM Institute Rijnhuizen using e-beam evaporation. The process is being optimized including parameters such as variation of the mirror's centre wavelength, the metal fraction, deposition parameters, and the layer composition. Reflectivities of 69.5 % are demonstrated at normal incidence, with values of 67 to 69% being routinely achieved, demonstrating the capabilities of the deposition process. Some evidence of smoothening to interface roughness values lower than the roughness of the initial substrate is given. Furthermore, investigation of the temporal behaviour of the coatings does not indicate any loss of reflectivity over an eight-month period. An analysis of the multilayer composition and the interface roughness is given. The reflectivity measurements have been carried out at the PTB facilities at the electron storage rings BESSY I and BESSY II in Berlin. The results of measurements at both facilities are found to be identical and accuracy is discussed in detail.

Keywords: Mo/Si multilayer coatings, normal-incidence reflectivity, electron-beam deposition, EUVL

INTRODUCTION

The ultimate performance of multilayer-coated EUVL projection systems depends critically on the multilayer coating technology and involves both the inherent wavelength-dependent physics properties of the multilayer system as well as the experimental ability to produce such a coating in a controlled process. An extensive optimization effort on the fabrication of Mo/Si multilayer systems is carried out at the FOM Institute Rijnhuizen using e-beam evaporation and ion-beam smoothening. The process is being optimized including parameters such as variation of the mirror's centre wavelength, the metal fraction, deposition parameters, and the layer composition.

At wavelength characterizations of these coatings are being performed at the PTB laboratory at the electron storage rings BESSY I and II. The activities are part of the EUCLIDES EUVL development project carried out by Carl Zeiss (Oberkochen, Germany) and ASML (Veldhoven, The Netherlands).

PEAK REFLECTIVITY AND UNIFORMITY

In order to maximize the throughput of multi-component EUVL optical systems, it is of paramount importance to obtain the best performance of the individual multilayer coatings. Thus, one of the most relevant properties of the coating process applied is the ability to achieve a high peak reflectivity. Figure 1 indicates the status of the reflectivity of our multilayer systems to date: a reflectivity of 69.5 %, as measured at 13.0 nm at an angle of 1.5° off-normal. The gain in reflectivity with respect to previously reported values of 64%[1], corresponds to a twice higher total throughput of a, realistic, ten-mirror EUV optical system. The level of reflectivity values which are routinely obtained in the coating process amounts to 67 to 69%. It is noted that these values are achieved using the standard composition of Mo and Si materials.

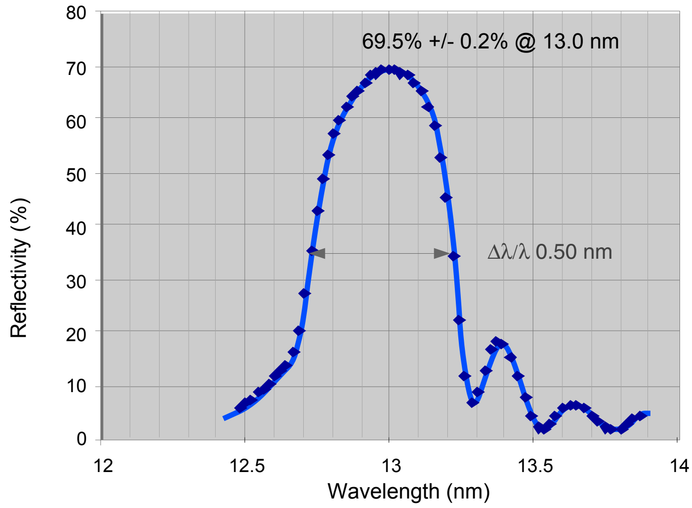

Fig. 1. Reflectivity of a Mo/Si multilayer mirror measured at 1.5° off-normal.

These coatings are applied to various flat and curved optics with control of the value of the d-spacing across the surface of the optic. The d-spacing uniformity which is achieved to date on test depositions for 6-inch substrates amounts to ±0.05% PV over a 170 mm area. This corresponds to a total thickness variation over this surface of 0.3 nm or single atom dimensions.

To obtain information about the composition of the multilayer, we performed grazing incidence specular reflectivity measurements using Cu-K_α radiation ($\lambda = 0.154$ nm) and fitted the signal to a stack of two, respectively

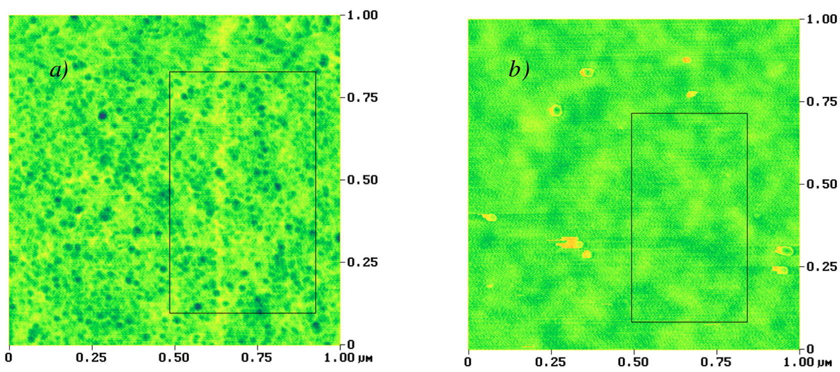

Fig. 2: AFM scans of an uncoated (a) and a coated (b) Zerodur surface.

four layers per period. The four-layer model, described in detail in ref. 2, takes Mo_xSi_y interlayers into account and leads to a more appropriate fit of the experimental reflectivity data. The analysis shows 0.8 nm thick interlayers at both boundaries. The near-normal incidence reflectivity can also be described using this four-layer model.

The interface roughness determined from the Cu-K reflectivity scans is 0.23 to 0.30 nm rms and is constant through the entire stack. This is concluded from high-resolution transmission electron micrographs and from AFM data. Figure 2b shows an AFM scan of the surface of the top layer of a 50 period coating on a Zerodur substrate. It shows a mean roughness of 0.13 nm. Figure 2a shows a scan from the same, yet uncoated substrate of which the mean roughness amounted 0.21 nm. This reduction of the roughness after coating indicates that the substrate roughness can be reduced by the multilayer coating process. This effect might be exploited for the fabrication of ML mask blanks and the smoothening of the smaller blank defects.

AT WAVELENGTH REFLECTOMETRY

Reflectometry was performed with the PTB-reflectometer[3] at the PTB VUV-radiometry beam line[4] at BESSY I. For the demands of the EUCLIDES project, the relative uncertainty of about 1 %, achieved before, was not sufficient. An important step forward was achieved by optimizing the diameter of the beam entrance aperture of the reflectometer. Increasing the aperture diameter from 0.3 mm to 1.2 mm led to an improved stability of the beam intensity due to a decreased sensitivity to horizontal drifts of the synchrotron radiation source point. A dedicated measuring cycle, e.g. first the determination of the peak wavelength from a wavelength scan and second a measurement directly at the on-line evaluated peak wavelength, further improved the statistical reproducibility of the maximum reflectance. In the region of the main maximum the relative standard uncertainty of the reflectance is 0.25 %. The individual contributions to the total relative uncertainty are summarized in table 1.

<table>
<tr><td colspan="3">Peak reflectance</td></tr>
<tr><td colspan="2">intensity fluctuation</td><td>0.12 %</td></tr>
<tr><td rowspan="2">spectral purity</td><td>higher diffraction orders</td><td>0.06 %</td></tr>
<tr><td>diffuse scattered light</td><td>0.2 %</td></tr>
<tr><td colspan="2">total relative uncertainty of the peak reflectance</td><td>0.25 %</td></tr>
</table>

Wavelength	
comparison with Kr 3d5/2-5p resonance energy	0.012 %
vertical drift of source position	0.05 %
total relative uncertainty of the peak wavelength	*0.05 %*

Tab. 1. Uncertainty contributions for measurement of peak reflectance and peak wavelength.

By measuring the same sample several times, a relative standard deviation of the reflectance of 0.2 % was observed over a period of 6 months. Typical reflectance curves, observed for mirrors coated at FOM are shown in figure 1. The absolute wavelength scale was checked at the Kr 3d5/2 to 5p resonance at 13.595 nm with a relative uncertainty of 0.012 %, which is due to the determination of the peak position (0.006 % relative) and the uncertainty of the Kr resonance wavelength (0.012 % relative).

The reproducibility of the peak wavelength was checked by measuring the same sample several times. Without correcting the vertical drift of the electron beam, which influences the apparent energy scale, a relative deviation of only 0.05 % was observed over a period of 6 months. Within one week, the typical reproducibility of the peak wavelength is better (0.006 %). After the shutdown of BESSY I at the end of 1999, reflectometry is continued at the PTB laboratory at BESSY II [5]. Therefore, the plane grating monochromator (PGM) beamline at the PTB U180 Undulator [6] has been characterized for reflectometry around 13 nm. A representative result of that characterization, the relative contribution of second order photons, is shown in figure 3. It demonstrates that further

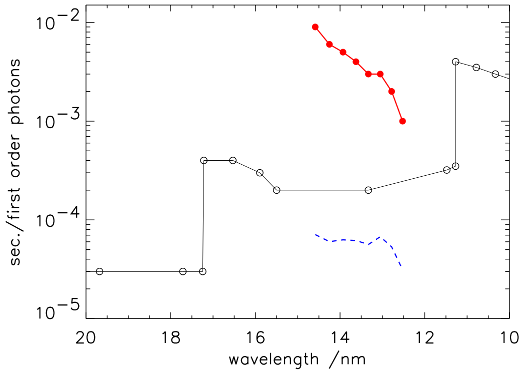

Fig. 3. Relative contribution of second order photons at the PGM at BESSY II; measured contribution without filter (filled circles) and the projected contribution with filter (dashed line). The values from BESSY I with filter are shown for comparison (open circles).

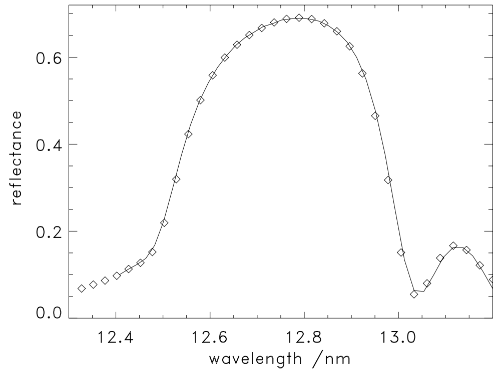

Fig. 4. Comparison of the reflectance of a Mo/Si multilayer measured at BESSY I (line) and BESSY II (diamonds).

improvements of the spectral purity have been achieved. The consistency of reflectometry results has been proofed by measuring the same mirror at BESSY I and II. The result is shown in figure 4.

TEMPORAL STABILITY

An important issue is the temporal stability of the coatings. Figure 5 shows repetitive measurements of the reflectivity of two sets of multilayer samples, namely one with a silicon top layer (plus the native SiO_2 caused by exposure to air) and one with a carbon capping layer. Within the measurement uncertainty of ±0.2%, both sets show no loss of reflectivity over the eight-month period investigated, indicating that the deposition process results in stable multilayer systems. In addition, no measurable change of the d-spacing of the coatings could be observed. During this eight-month period all samples were stored in air under normal room conditions.

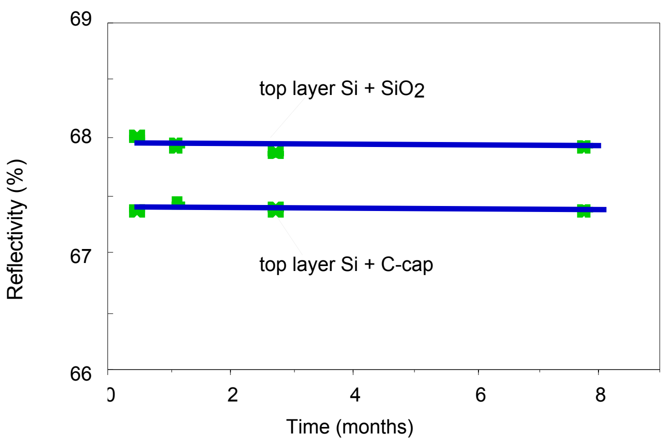

Fig. 5. Temporal stability of the reflectivity of a standard Mo/Si multilayer and a C-capped Mo/Si system.

EUVL OPERATIONAL WAVELENGTH

In a practical EUV imaging system the throughput is not only determined by the peak reflectivity, but also by the bandwidth of the system. Both calculations and measurements on experimental multilayer coatings that we produced indicate that the peak reflectivity reduces at longer wavelengths, while the bandwidth increases, factors that obviously have opposite effects on the throughput. Figure 6 shows the calculated integrated reflectivity and therefore the throughput of the optical system in the case a source with a wavelength independent emission spectrum is applied.

The main conclusion of the study, described in more detail in ref. 7, is that the maximum integrated reflectivity of a Mo/Si system is 50% higher than any Mo/Be system. Furthermore, the maximum in integrated reflectivity for a Mo/Si system is obtained at λ = 14.4 nm and not close to the Si-L edge. This phenomenon is caused by the fact that the increase in bandwidth for longer wavelengths dominates over the decrease in peak reflectivity. For a practical EUVL system, the use of Mo/Si for larger wavelength has considerable advantages, namely higher tolerances on the fabrication of the coatings (wavelength matching) and a reduced influence of flare, which is inversely proportional to the wavelength[8].

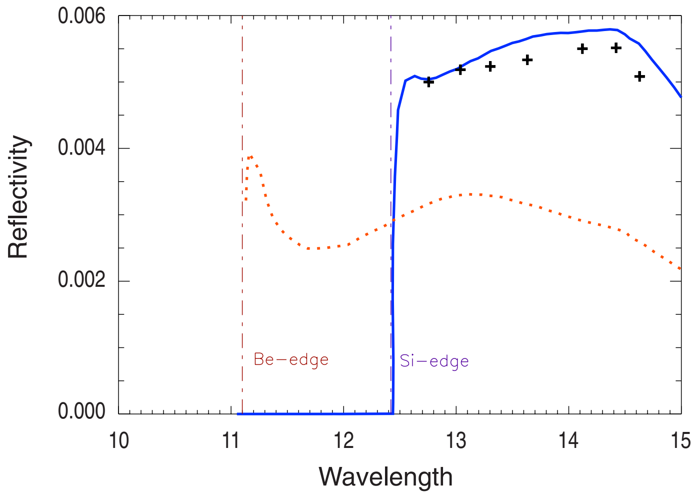

Fig. 6. Integrated reflectivity for a 10 mirror EUV system: calculated data (solid and dotted lines) and data extrapolated from measured reflectivity curves (+).

VOLUME COATING PRODUCTION

The relatively slow deposition speed of our particular e-beam deposition system is due to the multi-purpose R&D nature of the facility, which was not set-up for achieving high productivity. For the present day deposition a low power electron gun is being used (about 1/10 of the power of e-guns currently available). Since the evaporation flux scales more than linear with the e-gun power, a significant increase of the deposition speed can easily be obtained. Combining this with other features known from commercially available equipment, a full stack deposition within one to two hours is calculated to be feasible. An increase of the productivity of the process, while keeping the properties of the coating at the current high level, is currently being assessed.

CONCLUSIONS

In this work we demonstrated that a near-normal incidence reflectivity of > 69 % for a wavelength of 13 nm can reproducibly be obtained using a deposition process based on e-beam evaporation. Demonstrations of a coating uniformity of ±0.05% over a 170 mm area have been given. These coatings are stable in time, both in reflectivity and in d-spacing over the period of eight months investigated. First evidence of the ability to smoothen initial substrate roughness is given.

For a ten-mirror optical system, Mo/Si coatings for 14.4 nm were calculated to have the highest integrated reflectivity, assuming an EUV light source with a 'white' spectrum. From the point of view of multi-element, high-throughput optics, this wavelength is the optimal choice. The calculations are confirmed by reflectivity measurements of optimized Mo/Si multilayer coatings produced with our process.

A comparison of reflectivity measurements of Mo/Si mirrors at the at-wavelength reflectometry facilities of PTB at both electron storage rings BESSY I and II shows perfect consistency between these two facilities.

ACKNOWLEDGEMENT

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